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LOW-DIMENSIONAL MODELS FOR THERMOCAPILLARY CONVECTIVE FLOWS IN CRYSTAL GROWTH PROCESSES

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Research has been directed toward the following tasks:

1. CONSTRUCTION OF LOW-DIMENSIONAL MODELS

We have successfully constructed and validated low-order models for transitional forced, free, and thermocapillary convective flows in cavities and channels ([5], [6], [7], [8], [9], [10], [11], [12]) and we have extended the methodology to problems with moving geometry and deformable meshes. Proper orthogonal decomposition has been applied to oscillatory thermocapillary convection data obtained by J. Xu and A. Zebib (J. Xu and A. Zebib, 1996 International Mechanical Engineering Congress). The spatial eigenfunctions were determined by applying the method of snapshots to numerical solutions of the full model. In all cases the most energetic modes contain the large scale features of the flow, while modes with lower fluctuation energy levels capture smaller scale features.

During the past two years we have developed computational tools for the Karhunen - Loeve decomposition (POD) of 2-D and 3-D oscillatory convective flows and the construction of low-dimensional dynamical models.

2. DIRECT NUMERICAL SIMULATION OF THERMOCAPILLARY FLOWS IN RECTANGULAR CAVITIES

Two configurations were investigated: a) differentially heated open cavities of aspect ratio (width/height) $A = 1, 2, 4$ and b) open shallow cavities with spatially periodic temperature distribution imposed on the free surface. In case (b) the governing equations are solved in a computational domain consisting of a single module with periodic boundary conditions on the side boundaries. All simulations are time-accurate and they incorporate the flexibility of the free surface.

The work on low-Prandtl-number thermocapillary convection in cavities of aspect ratio $A=2$ complements our previous study of thermocapillary convection in square

cavities ($A=1$) that has been confirmed by A. Zebib at Rutgers University and by Ken Ball at Texas University at Austin. The new results for $A=2$ are at variance with the results of Chen and Hwu (Chen, J.C. and Hwu, F.S., "Oscillatory thermocapillary flow in a rectangular cavity," Intl. J. Heat Mass Transfer, pp. 3743-3749, 1993). Free surface deflections are found to be several orders of magnitude smaller than those reported by Chen and Hwu. Furthermore, steady solutions are obtained in cases when Chen and Hwu report oscillatory conditions.

3. ANALYSIS OF INTERFACIAL INSTABILITIES

In the first year of our investigation we have focused on interfacial instabilities in two-layer Poiseuille flow. Initially we have neglected temperature and viscosity fluctuations [1]. In the second year of our investigation we have incorporated the effects of temperature and viscosity fluctuations in our analysis [4]. The results indicate that temperature and viscosity perturbations have a pronounced effect on the interfacial mode of instability. This is in contrast to our findings on the stability of plane, single-layer, Poiseuille flow for liquids exhibiting exponential viscosity-temperature dependence [3].

In [3] it was found that in shear instability mode the critical Reynolds number decreases compared to isothermal flow conditions. An imposed wall temperature difference is always destabilizing. The influence of Prandtl number, temperature fluctuations and viscosity fluctuations on the flow stability/instability is found to be small. However, their influence on the margin of stability, as measured by the imaginary part of the wave speed, is appreciable for small wavenumbers.

4. EXTENSION OF THE PRANDTL-BATCHELOR THEOREM

Convective flows in cavities are characterized by the presence of single or multiple regions of closed streamlines. In [2] we have presented new results for the structure of closed eddies in thermally driven flows of low Prandtl numbers and high Grashof numbers. The analysis provides an extension of the classical Prandtl-Batchelor theorem. Numerical calculations given for laterally heated rectangular cavities are in excellent agreement with the developed theory.

Third Microgravity Fluid Physics Conference, Cleveland, OH, June 13-15, 1996, NASA CP 3338, pp. 325-330.

[10] A. Liakopoulos and P.A. Blythe, "Low - dimensional dynamical models of transitional convective flows," Bull. Am. Phys. Soc., Vol. 40, No. 12, 1995, p. 1955.

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[13] A. Pinarbasi and A. Liakopoulos, "Interface Stabilization in Two-layer Channel Flow by Surface Heating," submitted, Journal of Fluid Mechanics.

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[2] Low- dimensional models of transitional flows, University of Maryland, College Park, MD, April 26, 1996

PROJECT - FUNDED STUDENTS: 2 PH.D

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[2] Blythe, P.A., A. Liakopoulos and E. Haruta: "Thermally Driven Flows at Low Prandtl Numbers: An Extension of the Prandtl-Batchelor Theorem," *International Journal of Engineering Science*, vol. 33, No. 12, 1995, pp. 1699-1711.

[3] Pinarbasi, A. and Liakopoulos, A., "The Role of Variable Viscosity in the Stability of Channel Flow," *Intl. Comm. in Heat and Mass Transfer*, Vol. 22, No. 6, 1995, pp. 837-847.

[4] A. Pinarbasi and A. Liakopoulos, "On the Influence of Temperature and Viscosity Fluctuations on Interfacial Instability," *Intl. Comm. in Heat and Mass Transfer*, vol. 23, No. 4, 1996, pp.485-493.

[5] H. Gunes, A. Liakopoulos and R. A. Sahan, "Low-Dimensional Description of Oscillatory Thermal Convection: The Small Prandtl Number Limit," accepted, *Theoretical and Computational Fluid Dynamics*.

[6] R. A. Sahan, A. Liakopoulos H. Gunes, "Reduced dynamical models of non-isothermal grooved channel flow," accepted, *Physics of Fluids*.

[7] Sahan R.A., Gunes, H. and Liakopoulos, A., "Low-dimensional Models for Coupled Momentum and Energy Transport Problems," 1995 International Mechanical Engineering Congress, C. H. Amon, ed., HTD-Vol.319, pp. 1-15.

[8] Gunes H., Sahan, R.A. and Liakopoulos, A., "Low-Dimensional Representation of Transitional Buoyancy-Driven Flow in a Vertical Channel with Discrete Heaters," Proc. of the 1995 National Heat Transfer Conference, vol. 1, HTD-Vol. 303, A. Ortega and S.P. Mulay, eds., pp. 125-137.

[9] A. Liakopoulos, "Low-dimensional dynamical models of thermal convection,"